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Material and Process Technology Transition to Aging Aircraft

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Summary

A method is described that may be used to help ensure that a structural material or process will be successful when transitioned from the laboratory for replacement of existing materials and processes in an aging aircraft. Experience with laboratory and aircraft development programs has shown that five factors are essential for success in the technology transition process. An example is shown where the transition using this process was successful.

Introduction

Most aircraft operated commercially or in the military reach a state referred to as aging at sometime after entering operational service. Aging of an aircraft is not the same as it becoming obsolete. An aircraft may be obsolete before it reaches the aging state or, more typically, it reaches the state of aging before it is obsolete. A commercial aircraft is obsolete when it is no longer economically viable to keep it operational. A military aircraft is obsolete when its capabilities are no longer competitive with potential adversaries. The time when an aircraft reaches the aging state is usually much more difficult to determine. It is important to distinguish between the characteristics of the structure of a young aircraft and an aging aircraft. A young aircraft is one that continues to be airworthy with the maintenance program prescribed at the time of manufacture. The primary concern with a young aircraft is the potential for design errors that introduce unintentional high stresses in the structure that could lead to premature fatigue cracking incidents. When these are discovered the structure is modified to eliminate the problem. An aging aircraft may be characterized as one where the effects of corrosion and cracking from fatigue require modification of the maintenance program to retain adequate structural integrity. The word adequate here means that the expected number of failures would be less than one in a given fleet of aircraft. As an aircraft accumulates calendar time and flight time the effects of corrosion and cracking from fatigue, as well as accidental damage, leads to repairs on the aircraft. Cracking from fatigue can be so widespread that it degrades the integrity of the structure. When this occurs, the structure is said to be in a state of widespread fatigue damage or WFD and must undergo modifications to remove this problem. In addition, as an aircraft accumulates flight time, it may exceed its design life goal. Therefore, the maintenance program will require modification to include additional structural inspections. If the initial maintenance program requires modification from any of these events, then the aircraft may be considered to be in a state of aging.

No one should be surprised there are aircraft all over the world today in a state of aging. Economic considerations demand that aircraft be operated long beyond originally identified retirement times. One reason for keeping aircraft in the inventory is that technological advances allow currently designed aircraft to effectively perform their mission for much longer than previously possible. An aircraft, even when sold by one airline, sees extended life in another airline's operations. In the commercial sector, new aircraft tend to be evolutionary in their designs. Consequently, they are maintained in service until they are not economically viable to operate. The cost of new aircraft, particularly for the military, is enormous. Each new military aircraft is a revolutionary

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change from the previous model since the services must maintain combat effectiveness in an environment of ever-changing threats. Therefore, military aircraft stay in the inventory until they are operationally obsolete or they are no longer economically viable to operate.

Sustainment of an aircraft is the act of keeping it operational (i.e., airworthy). Maintenance of an aircraft (that is, the work done by mechanics in keeping it airworthy) is one aspect of sustainment. However, sustainment also includes the engineering analyses and tests needed to determine an adequate maintenance plan for the aircraft. Sustainment is life management. One task of sustainment is the determination of structural inspections based on damage tolerance principles. These inspections protect against failure from defects that could be in the structure because of manufacturing or from operational service. The approach for developing a damage tolerance derived inspection program is well documented. Another task of sustainment is the determination of the time of onset of fatigue cracking in the structure so widespread that the structural integrity of the aircraft could be compromised. Experimental evidence shows that fatigue cracks smaller than those that could be easily detected by current inspection methods could constitute WFD.

Today, the primary concern with aging aircraft is the cost of their sustainment. The commercial operators buy new aircraft when it becomes economically viable for them to do so. The aging aircraft problem, however, has often made itself known to both the commercial and military operators through failures of in-service aircraft. Both operators found the maintenance programs did not adequately protect aircraft as they progressed through their service lives. The failures in both commercial and military aircraft have been the primary factor that has changed rules and specifications that are the basis of their design. In many cases, the failures have identified threats to structural integrity that were not previously identified by the certification authorities. In many cases, the commercial failures have influenced the military specifications and the military failures have influenced the commercial aircraft rules. The new rules and specifications have lead to better maintenance programs that help alleviate many of the threats to failure that previously existed. However, the economic demand to fly these aircraft longer and longer has emphasized the need to re-examine these aircraft for the possibility of WFD, corrosion damage, and loss of damage tolerance capability through repairs.

It is difficult to determine the exact moment in time when an aircraft has reached the state of aging. However, all would agree that the costs associated with repairs or modifications from corrosion or cracking from fatigue would be an indicator of this condition. When these costs rise significantly, then the aircraft are certainly in that state. Chronological age is not always a good indicator of aging. However, since corrosion and fatigue are somewhat related to time in service, it does give some insight for the potential of this problem.

The time of development an aircraft is an important factor. Many development programs for materials in the fifties and sixties responded to aircraft performance needs. At this time, the material suppliers introduced high strength low ductility alloys in an attempt to satisfy the demand for less structural mass. Integrity programs such as USAF Aircraft Structural Integrity Program (ASIP) were either nonexistent or immature. Consequently, there was a lack of knowledge of threats to structural integrity

The structural engineer is fortunate to have many new technologies that could be used to help in meeting the challenges of aging aircraft. Some of these new technologies have been the basis for the sustainment of the aging fleets. There are several life enhancement techniques. An example of this is the cold expansion of fastener holes to improve their fatigue resistance. An outgrowth of this technology for the bushing of lugs has proved to be quite useful. The use of shot peening and laser peening have been shown to be useful for both crack and corrosion resistance improvement. Another technology is the use of boron composite repair of cracks and corrosion. This technology is in use extensively in the C-130 and C-141 aircraft to extend their useful lives. Protection approaches such as improved coatings and corrosion prevention compounds have found use in both military and commercial aircraft. Many aircraft have used replacement of existing materials to reduce the cost burden of maintaining structural integrity. One example of this is the replacement of the lower wing skins on the KC-135 aircraft. Other successful applications include:

Replacement of the F-16 479 bulkhead with 2097 aluminum lithium to replace existing 2024-T851

Replacement of the 7178-T6 KC-135 wing upper surface with 7075-T73

Replacement of the 7079-T6 C-5A fuselage skins with 7475-T761.

There are many other examples of successful transitions of technology from the laboratory to engineering and manufacturing development. Many of these successes were derived from a well-conceived plan or "road map" that formed the basis or criteria for technology transition. In general, these road maps have included programs directed at several levels of technology maturity. These levels are referred to as basic research, exploratory development, advanced development and manufacturing technology development. Most of the advanced development and manufacturing technology development program effort is directed towards the demonstration of the technology by means of the manufacture and testing of a specific piece of hardware.

A study of those successful road maps for transition of technology to engineering and manufacturing development reveals that that they had certain factors in common. These factors may be combined to form a criterion for the transition process to be successful. The importance of such a criterion for incorporating new structural technologies into an aircraft can be judged from transition experiences that were not successful. There are many examples that could be used to illustrate this. One example that has resulted in tremendous cost in money and productivity is the use of the high strength, low toughness 7XXX-T6 aluminum alloys in the fifties and sixties. The attractiveness of the weight reductions realized through their high strength caused the structural design engineers to utilize these alloys in many product forms and locations in the airframe. Therefore, in many cases they were improperly incorporated in engineering and manufacturing development. This was done without serious consideration of their susceptibility to failure from corrosion, stress corrosion cracking, and manufacturing and service induced defects. An example of use of this material based on strength considerations only is the skin of the lower wing of the KC-135, which was originally manufactured from 7178-T6. The inability to maintain the integrity of this structure in operational use because of fatigue cracking resulted in the replacement of the lower wing skin on more than 700 of these aircraft. The corrosion problems experienced in the 7075-T6 used in the center section of the C-141 wing resulted from inadequate sealing of the structure from the environment. This has caused and will continue to cause significant cost problems with that weapon system. The KC-135 and the C-141 are two of many that have experienced dramatic increases in their maintenance burden because these alloys were used in applications that were not compatible with their characteristics. The material problems are not restricted to aluminum. Improper use of magnesium, titanium, and steel has also resulted in high maintenance costs. In addition, to materials, processes have also experienced deficiencies in the transition criteria from the laboratory environment to engineering and manufacturing development as evidenced by the early manufacturing problems with the F-16 horizontal tail composite parts.

There are also many examples of faulty transition criteria led to serious problems in engines. As with the airframe, there are numerous examples where this has caused problems. One of these is the use of low ductility titanium in the F100 fan blades and fan disks. This usage led to extremely small critical flaw sizes and consequently a costly maintenance burden. This situation was corrected by a redesign. Another example was the use of powdered Rene 95 in the F-101 engine. The database for use of this material was generated from small coupons. However, when the process was scaled up to full size parts, the associated contamination degraded the properties to the point that a substitute material had to be used.

Another reason for establishing a criterion for transition is that there is a need for understanding the limitations on the technology. The laboratory demonstration program is seldom of sufficient scope such that provide confidence that all aspects of a given technology are suitable for operational use. Therefore, there is a danger that the engineer responsible for technology development may use it improperly. There is also the danger of an acceptable application.

It is the intent of this paper to describe the essential features of a criterion for successful transition of a structural technology from the laboratory to engineering and manufacturing development of a production aircraft. It has been demonstrated by service experience that the USAF Aircraft Structural Integrity Program (ASIP) [1] has the elements necessary to ensure that production aircraft developed from these requirements will be safe and economical to operate. The ASIP was initially developed in 1958 [2] to preclude the reoccurrence of some catastrophic failures that took place at that time. It was updated in the early seventies to include the currently used damage tolerance philosophy for structural design. All aircraft used or developed by the Air Force are subject to the requirements of the ASIP.

The ASIP provides the guidance for the engineering and manufacturing development phase of an aircraft. Consequently, its importance for this paper is that a structural technology may be judged against the elements of the ASIP to help determine if it is suitable for transition to this phase. Although the ASIP was conceived before the development of composites, the process may be easily tailored to these structures [3].

Technology Transition Criteria

From a study of the successful transitions of structural technologies from the laboratory to an operational aircraft, it was found that five factors constituted a common thread among these successes. In addition, it was found that these five factors were essential to the successful completion of the tasks of the ASIP. These five factors are:

1. Stabilized material and/or material processes

2. Producibility

3. Characterized mechanical properties

4. Predictability of structural performance

5. Supportability

In the listing, there was no attempt to establish a ranking of importance of these factors. A deficiency in any one of the factors could constitute a fatal defect.

It is readily seen that stabilized material and/or material processes are essential. With the time constraint on establishing the final allowables, any significant change in the material or processing could be disastrous. However, it is not expected that all of material and processing specifications be completed at the start of material or process substitution process. It is adequate to have preliminary documentation of the following:

Material qualification and acceptance specifications

Processing specification and acceptance standards

Manufacturing instructions

This factor must address the issue of corrosion. It is expected at the start of the material and substitution process that the corrosion resistance of the material be characterized. In addition, the analyst should establish the requirements for cladding, anodizing, priming and top coating.

Several producibility considerations must be addressed. First, the material supplier must be capable of supplying the material in appropriate quantity and forms. Experience has shown that the time required for scaling up material sizes or changing product forms is generally not compatible with time available to implement the desired change. Even in the case of large, but state of the art, forgings care must be exercised because the properties are extremely configuration dependent.

Another producibility requirement is to use the technology to fabricate detail parts and assemblies. For this purpose, generally full-scale parts are required. This fabrication must cover the range of forming parameters and material heat treat conditions that are appropriate. In rare cases, fabrication of subscale parts could be acceptable if the behavior of the full-scale parts can be confidently predicted.

Inspectability through the manufacturing process is another essential issue in the producibility factor. If conventional methods are appropriate then they must be identified and approximate capability established for the critical locations. If new methods are required then they must have progressed beyond the laboratory stage and have a demonstrated capability to perform the intended inspections.

It must be demonstrated that the manufacturing process is compatible with the shop environment. The government environmental standards that are imposed on the manufacturing facility may have a severe impact on the allowed processes. This problem is aggravated by the fact that these standards are rapidly changing and becoming more severe.

Of all the factors in the transition criteria, characterized mechanical properties is the most difficult to identify the specific requirements. There are three guiding principles that should be used to establish these requirements. One of these is that the final characterization should be complete before the design process is complete. Another is that at the start of the design process the properties should be established with sufficient accuracy to determine the weight of the structure. The final guideline is that property investigation should be extensive enough in scope to preclude the possibility that the technology will fail to reach its intended purpose. In some cases this may require an evaluation of the material or process characteristics when exposed to nuclear and/or non-nuclear threats. The initial emphasis should be on the assessment of many characteristics of the technology rather than an in-depth assessment of any single one of them.

As a minimum, the following mechanical properties must be evaluated in the presence of environmental effects:

Strength - Coupon tests are required for tension, compression, shear, and bearing for yield and ultimate as appropriate

Modulus - Coupon tests as appropriate are required to derive the stress strain relationship

Elongation - Coupon tests as appropriate are required

Fracture Toughness - For metals, K_{Ic}, K_c data and R curve data are required as needed for establishing design stresses

Crack Growth Rate - For metals, data required for range of values of R expected in operational aircraft

Dimensional stability - includes data for potential creep effects to be expected in operational aircraft and thermal coefficient of expansion data

Stress Corrosion Cracking - Either K_{Iscc} data or stress

Threshold data required for thickness and product form combinations expected to be found in the operational aircraft

For many technologies, it is not adequate to base the success of a technology on coupon data. For example, in many composite structures the interlaminar stresses produce critical failure modes that can not be confidently interrogated in the coupon level tests. It is expected that appropriate element and subcomponent tests (i.e., building block tests) be performed. Generally, strength, durability, and damage tolerance testing will be performed in these building block tests.

The three guidelines stated above are believed to be adequate to determine the quantity of data needed. However, some additional guidance may be useful. For the coupon strength tests, a minimum of four tests from each of four material lots would satisfy the requirement for transition. This database would not be adequate for the generation of allowables as recommended in MIL-HDBK-5. However, the database should be adequate for establishing the Weibull parameters and making usable preliminary estimates of the allowables. For fracture toughness, the contractor should supply metal materials with fracture toughness with a minimum guaranteed. Therefore, the tests should demonstrate that there is a balance between structural performance and economics of procurement. For rates of crack growth in metal structures (i.e., da/dn data) average properties are acceptable. However, multiple tests are needed to estimate the variance in this data. If the analyst judges these variances as excessive, then there should be a reassessment of the material and process specifications to try to reduce the scatter in this property.

Prediction of structural performance is an important factor because the full-scale static, durability, and damage tolerance tests are very expensive. Therefore, there should be reasonable expectation that the analyses and design development tests preceding these tests would lead to success. Further, and even more important, is that a structure developed under the ASIP will provide safe and economic operation of production aircraft. Generally, the predictability of structural performance can be validated with a subcomponent test. That is, a section of a wing or fuselage etc. would be adequate. These tests must be carefully designed to ensure that all potential critical load paths are assessed.

Usually the key to satisfying the predictability factor for structural performance is sound analytical procedures. This is the hallmark of currently used metallic materials. For these materials, critical strength failure modes in tension, compression, shear, and bearing are predictable. Further, the availability of crack growth laws for metals permits the damage tolerance capability to be established. For composite structures, the analytical procedures are still emerging. Difficulties persist in the prediction of interlaminar stresses and the growth of delaminations derived from impact damage. However, these problems can be handled with empirical methods. When empirical processes can be used confidently then this factor can be satisfied.

The damage tolerance era, which started in the early seventies, has helped to reduce some of the supportability requirements for currently designed aircraft. However, the supportability factor is still a major consideration because of accidental and battle damage. Any new structural concept forces the maintainers and the operators to prepare to make repairs. This places demands on supply lines and training of personnel. The establishment of facilities with trained personnel normally lags the development of the technology significantly. For example, the composite repair capability for in-service aircraft is only now maturing but the composite technology has been transitioned to operational aircraft for approximately two decades. Further, the acceptance of a new technology by the maintainers and operators may place a large economic burden on them. This could be difficult to justify. Consequently as a prerequisite for transition, the repairs associated with the technology must be at least conceptually developed. That is, the repair must be viable in the using command environment and must be manageable from economic considerations.

In addition to the repair aspect of supportability, inspectability must be addressed. This includes both manufacturing and in-service inspections. If the inspections required are not viable with existing equipment then there must be reasonable assurance that these inspections can be made when they are needed.

Example of Successful Transition of Technology

Previous and current inspection programs have revealed that the vertical tail attachment pads in the F-16 Fuselage Station 479 bulkhead are significantly cracked in the majority of early aircraft. Figure 1 shows the configuration of the bulkhead and Figure 2 shows the area where cracking has been experienced. The depot responsible for F-16 maintenance has considerable experience in the eddy current inspection for these cracks and have established appropriate guidelines for the disposition of cracks found in operational aircraft. The root cause of this cracking is high stress concentration inherent in the detail design compounded by increased usage severity precipitated by weight increases in the aircraft without compensating structural modifications. The stresses at the point of crack initiation are extremely high although they do decrease with increasing crack depth. These high stresses cause early cracking in the structure.

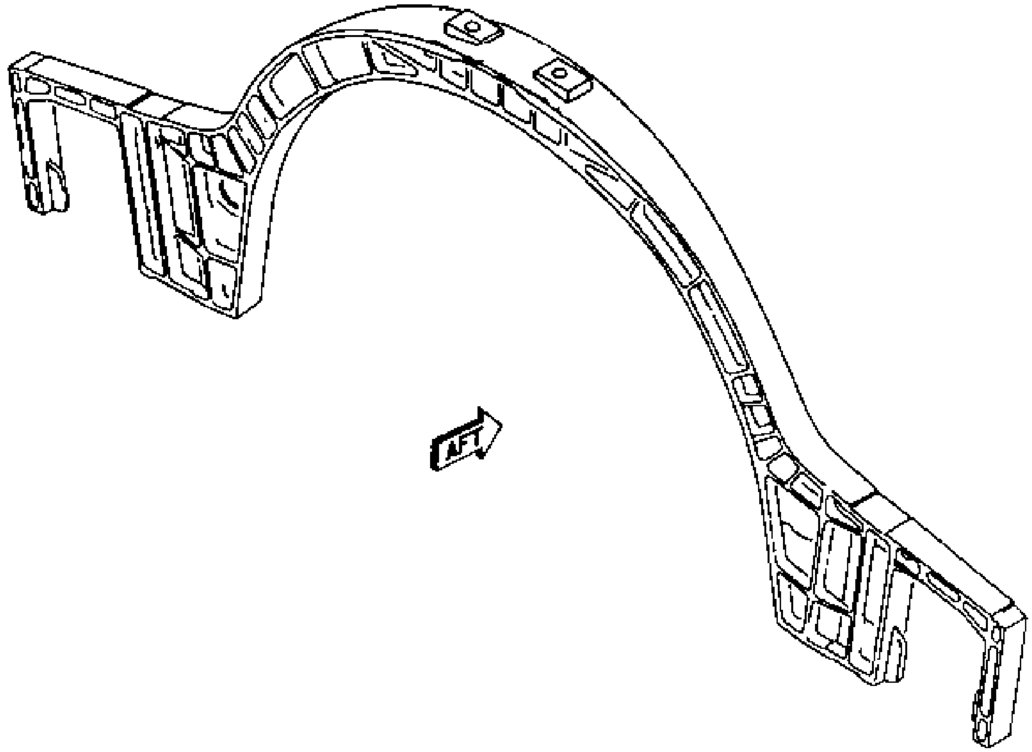

Figure 1 The Fuselage Station 479 Vertical Tail Attachment Bulkhead

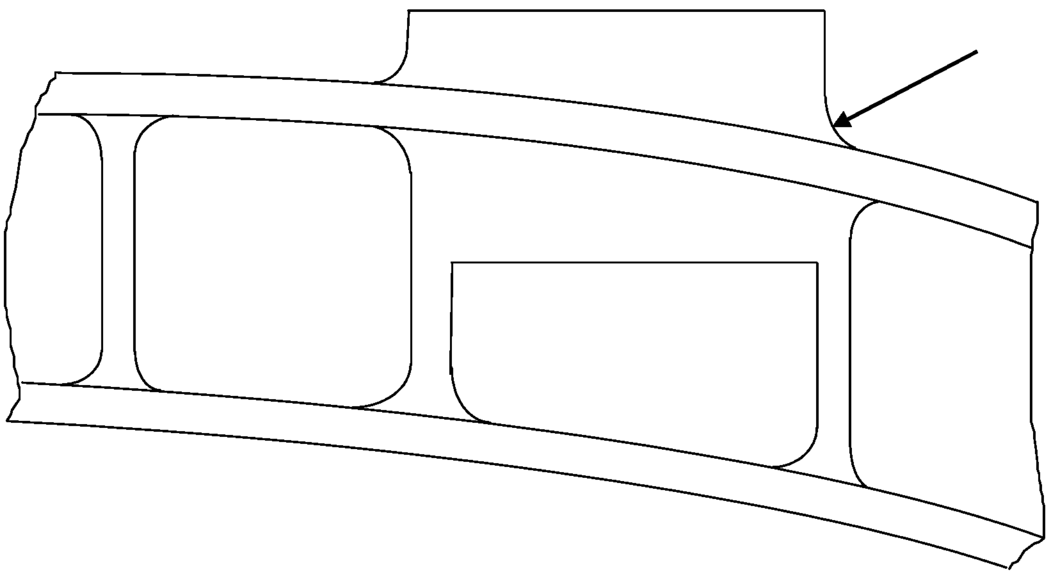

Figure 2 The Fuselage Station 479 Bulkhead Area of Cracking

Normally, the USAF would not fly these aircraft with known cracking. In this situation the situation is relieved because the vertical tail structure has been analytically shown to have adequate fail-safety in the event of a failure of the F.S. 479 bulkhead.

Preliminary studies showed that the fracture toughness of aluminum lithium was high enough such that a crack would grow through stable propagation through the high stress concentration region. This feature enabled the bulkhead to remain in service considerably longer than the baseline bulkhead. However, it would be expected to have crack indications early in its life because of the inherent high stress at the radius. Its structural integrity would be ensured through fail-safety.

Consequently, these studies indicated that the use of a new bulkhead material identified as 2097 aluminum lithium would provide considerable improvement in the structural integrity in this location. The original material was 2024-T851 aluminum. The USAF requested the contractor to develop a program around the five elements of technology transition for a new material or process. These five elements are; (1) stabilized material and processes, (2) producibility, (3) characterized mechanical properties, (4), prediction of structural performance, and (5) supportability.

The 2097 material satisfies the first element - stabilized material and material processes. The material specification has been finalized and significant amounts of the material have been produced to this specification. All of the replacement components will be procured to this specification. The boundaries of the processing parameters have been examined and no significant degradation of properties has been observed.

The second element - producibility has been satisfied in that full-scale parts have been fabricated with the same tools that were used to fabricate the conventional aluminum parts. There have been no toxicity issues found for the handling and machining of the forged part. Also, the scrap disposal is feasible without contamination of the conventional alloys.

The third element - characterized mechanical properties was completed. Since the final strength properties had not been characterized to the MIL-HDBK-5 standards, the design team used S-values for strength characterization. The strength properties that are significant to this application for the 2097 material exceed the strength of the baseline conventional aluminum. The fracture properties are well characterized for the “long crack” analyses that would be used for this bulkhead. The corrosion resistance has been successfully demonstrated through the EXCO test procedure. Also, the stress corrosion cracking thresholds are in excess of the baseline material, which has performed well with respect to this issue.

The fourth element - predictability of structural performance had to be satisfied by a combined analysis and test program. Conventional linear fracture mechanics approaches were not able to completely characterize the growth of small cracks. The problem was that the very high stress concentration in the area of cracking increased the strains beyond the yield point. Therefore, the contractor used component testing to augment the analytical results to ensure that the new material was significantly better than the baseline material.

The fifth element - supportability was found to be adequate. Aluminum lithium has the characteristic that the fracture face is quite rough compared with the baseline material. However, this should not be an inhibitor to making an inspection for cracks in operational aircraft. This was demonstrated through component testing.

Therefore, the team recommends that the aluminum lithium material be used for the F.S. 479 bulkhead replacement.

Conclusions

This paper has discussed the five factors believed to be essential for successful transition of a technology from the laboratory to successful application on operational aircraft.

Experience has shown that deficiencies in these factors will result in a less than satisfactory operational performance. It is evident that there is considerable judgment involved in addressing each of these factors. However, it is believed that the effort required in making this judgment is justified when the consequences of using a deficient technology are considered.

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